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UNDERWATER FLOW VISUALIZATION TECHNIQUES

By

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ABSTRACT. Flow visualization techniques useful for studies of models and live fish, have been developed by the Naval Ordnance Test Station in conjunction with the Fisheries Research Institute of the University of Washington. General patterns of the flow around fish are shown by means of flow marker techniques. Because of the incompatibility of the fish with flow markers, these techniques were not entirely successful. Boundary layer phenomena are shown by means of a Schlieren technique. The Schlieren technique appears to be a powerful new tool for boundary layer studies.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

29 August 1961

U. S. NAVAL ORDNANCE TEST STATION

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FOREWORD

The purpose of this report is to describe the flow visualization techniques developed by the Naval Ordnance Test Station in conjunction with the Fisheries Research Institute, University of Washington, Seattle. Principal personnel involved in the project were: Prof. Joseph Kent (UW), hydrodynamic program; Prof. Allan Delacy (UW), fisheries program; and the author (NOTS), photo-optical program.

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INTRODUCTION

This report describes the flow visualization techniques developed by personnel of the Naval Ordnance Test Station (NOTS) in conjunction with personnel of the Fisheries Research Institute, University of Washington (UW), Seattle, Washington.

The problem of flow visualization was separated into two distinct areas. The first problem was to show the general flow of the water around the fish's body including the vortices in the wake of the fish. The second problem was to show the flow or condition of the boundary layer adjacent to the skin of the fish.

Most of the efforts to supply a flow visualization technique for the general flow problem revolved around the use of neutrally buoyant beads called flow markers (Ref. 1). Three basically different bead techniques were developed and used to show the general flow pattern of the water generated by a swimming fish. The techniques showed promise, but unfortunately none of them were more than partly successful. One technique involved styrene beads (Ref. 2) suspended in still water and the other two methods used latex beads (Ref. 3) in moving water (Ref. 4).

Other minor experimentation was done with dye markers, but they were found to be too difficult to handle in the available flumes. The birefringent solution bentonite was also considered; although it was previously used with small fish in small tanks, the large light losses encountered in the milky liquid in deep tanks precluded its use for large fish.

Boundary layer flow was quite successfully shown by a Schlieren technique. This optical technique makes visible local refractive changes in the test medium. These changes were induced underwater by thermal changes in the boundary layer caused by a transfer of heat from a warm fish to cool water. This technique provided many excellent pictures of laminar and turbulent boundary layer phenomena.

FLOW MARKER TECHNIQUE

MOVING-WATER, SINGLE-PHOTOGRAPH TECHNIQUE

The moving-water experiments were conducted in a flume 22 ft long by 15 inches wide by 15 inches deep. A 6-ft section of the flume was made of Lucite so that the fish could be observed from either the side or bottom of the flume. A 45 deg mirror located underneath the test section eased the photographic problem. A barrier prevented the fish from swimming too far upstream, and a downstream electric fence encouraged the fish to swim far enough upstream to avoid the electric current. Thus, the fish was forced to swim in the test section for many minutes at preselected speeds.

The single-picture technique indicated flow by means of a photograph blurred by motion of the beads immersed in the moving water. A rather large quantity of latex beads (3-mm diameter) were released upstream and allowed to drift downstream past the fish. At the proper instant, a single photograph of the fish and beads was taken with a 4X5 Graflex camera with the shutter set at a 1/30-sec exposure. At this slow shutter speed, the relatively slow-moving fish usually photographed clearly, and the beads, traveling at high velocities, photographed as streaks. The streaks showed the direction and relative speed of the water flow. Figures 1 and 2 show the type of picture obtained with this method. In the fish photograph, special side lighting is used so that only a thin plane near the lateral line of the fish and the beads in this plane are shown. Since the fish took evasive action when the beads were released, it proved to be hard to coordinate the fish and beads and obtain good photographs.

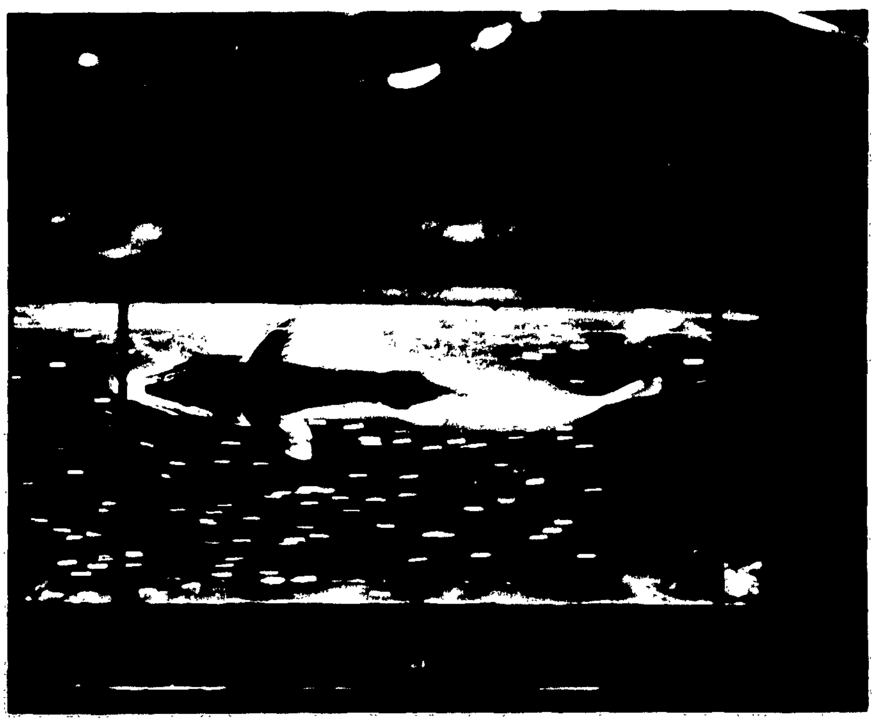

FIG. 1. Fish; Moving-Water, Single-Picture Technique.

FIG. 2. Cylinder; Moving-Water, Single-Picture Technique.

Flow pictures obtained in moving water appear completely different from photographs obtained in still water. The vortical motion of the water shows more clearly in a still-water picture since the vortical motion is essentially a circulation around a fixed point rather than a translation of the water. The vortical motion in the moving water appears, to a fixed camera, to be a sinusoidal motion rather than a circulation phenomenon. A camera moving with the water would picture the event the same as flow about a moving fish in still water would appear to a fixed camera.

MOVING-WATER, MOTION-PICTURE TECHNIQUE

Another moving-water technique used two synchronized motion picture cameras in a stereoscopic arrangement. A small number of latex beads were released in the flume and, since they were quite large (3-mm diameter), individual beads could be followed from frame to frame and their position versus time determined. Figure 3 is a picture taken with this technique. By operating the camera continuously,

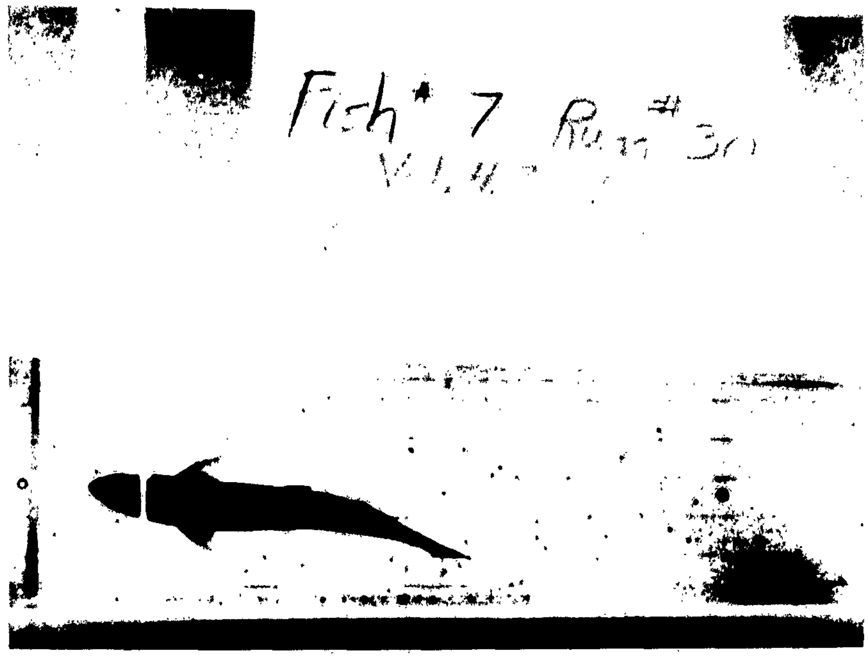

FIG. 3. Fish; Moving-Water, Motion-Picture Technique.

data was accumulated fairly quickly; since the fish found it impossible to consistently avoid the beads, some fair records were obtained. Unfortunately, reduction of the data was very expensive and time-consuming. This difficulty forced the development of a still-water technique to ease the reduction problem.

STILL-WATER, MOTION-PICTURE TECHNIQUE

A large tank (Fig. 4), 22 ft long by 30 inches wide by 18 inches deep, was constructed and used for both Schlieren studies and the styrene-bead general flow studies. The top of the tank was located 10 ft above floor level so that the Schlieren test section could be adapted to the vertical Schlieren system (described in next section). This also elevated the tank so that the camera used for the flow marker technique could obtain an unobstructed view (over other equipment) of the test section located 35 ft away (Fig. 5). The remote location of the camera minimized calibration problems since it reduced perspective distortions. In fact, the one camera can replace the previous two cameras used in the stereoscopic system. The one

FIG. 4. Static Flume, Schlieren and Still-Water Techniques.

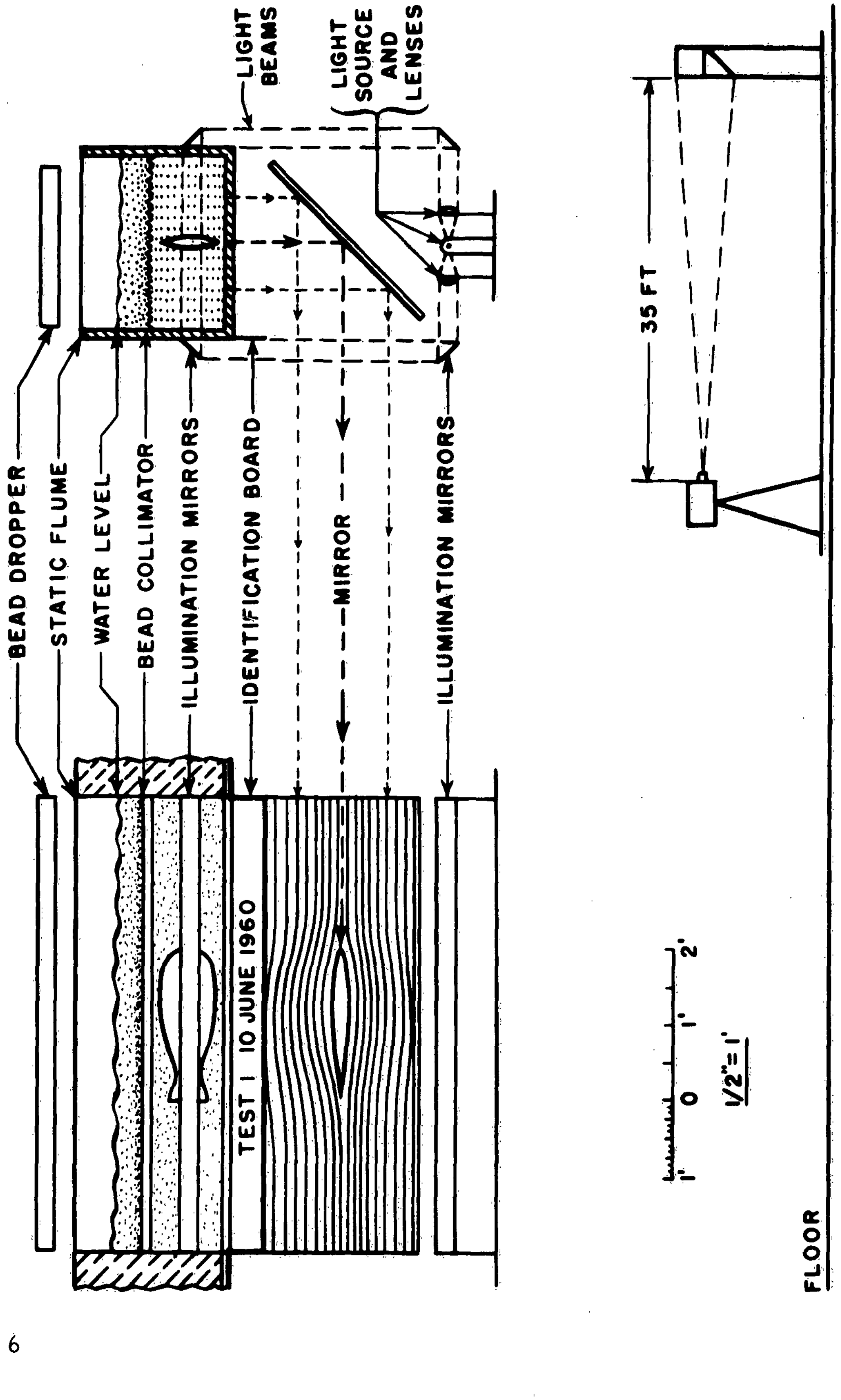

FIG. 5. Still-Water, Motion-Picture System.

camera recorded on every frame a side view of the fish, an identification board, a bottom view of the fish (as seen through a 45 deg mirror located underneath the Lucite section of the tank), and a calibration grid located on the bottom of the tank.

The still-water technique indicated flow by a distortion of parallel lines of immersed styrene beads as the fish swam parallel to the lines. A wooden mechanism (Fig. 6) located on top of the tank was used to drop small, 1-mm diameter styrene beads. This device dropped a very uniform pattern of beads into the water. The beads dropped slowly through the water, and a series of underwater V-shaped troughs collimated the slowly dropping beads into long thin planes. Two sharply defined superimposed beams of light (one projected from each side of the tank) illuminated the fish and planes of beads (see Fig. 5). The horizontal beams were located, in elevation, at the expected position of the lateral line or middle level of the fish. The beams covered the length of the tank, and were approximately 2 inches thick. Thus, the thin beams of light outlined the fish and illuminated the beads in the same horizontal plane as the lateral line of the fish. This type of illumination transformed the parallel planes of beads into parallel grid lines that were distorted by the flow around the fish. Figure 7 is a picture procured with this method.

The bottom view of the fish contains almost all of the data. The only purpose of the side view is to gain a rough idea of the relative elevation of the fish with respect to the beams of light and to observe if the fish is swimming in a normal manner. Some fish have been observed to swim in a highly irregular fashion with their heads very low and tails very high. The black line across the side view of the fish is a mirror used to reflect a light beam into the tank. The camera lens is located in the shadow of the near mirror so that the beam on the other side of the tank does not strike the camera lens.

Unfortunately, the fish objected strongly to the beads and no satisfactory way was found of inducing the fish to swim uniformly from one end of the tank to the other. When the beads were omitted, the side beams turned off, and the tank back-lighted from the top, then the fish would cooperate and many excellent runs were taken of the general swimming behavior of the fish (Fig. 8).

SCHLIEREN VISUALIZATION OF BOUNDARY LAYER

SCHLIEREN TECHNIQUES AND EQUIPMENT

No attempt is made to describe the Schlieren theory or techniques in full, since this is a recognized technique in aerodynamic research.

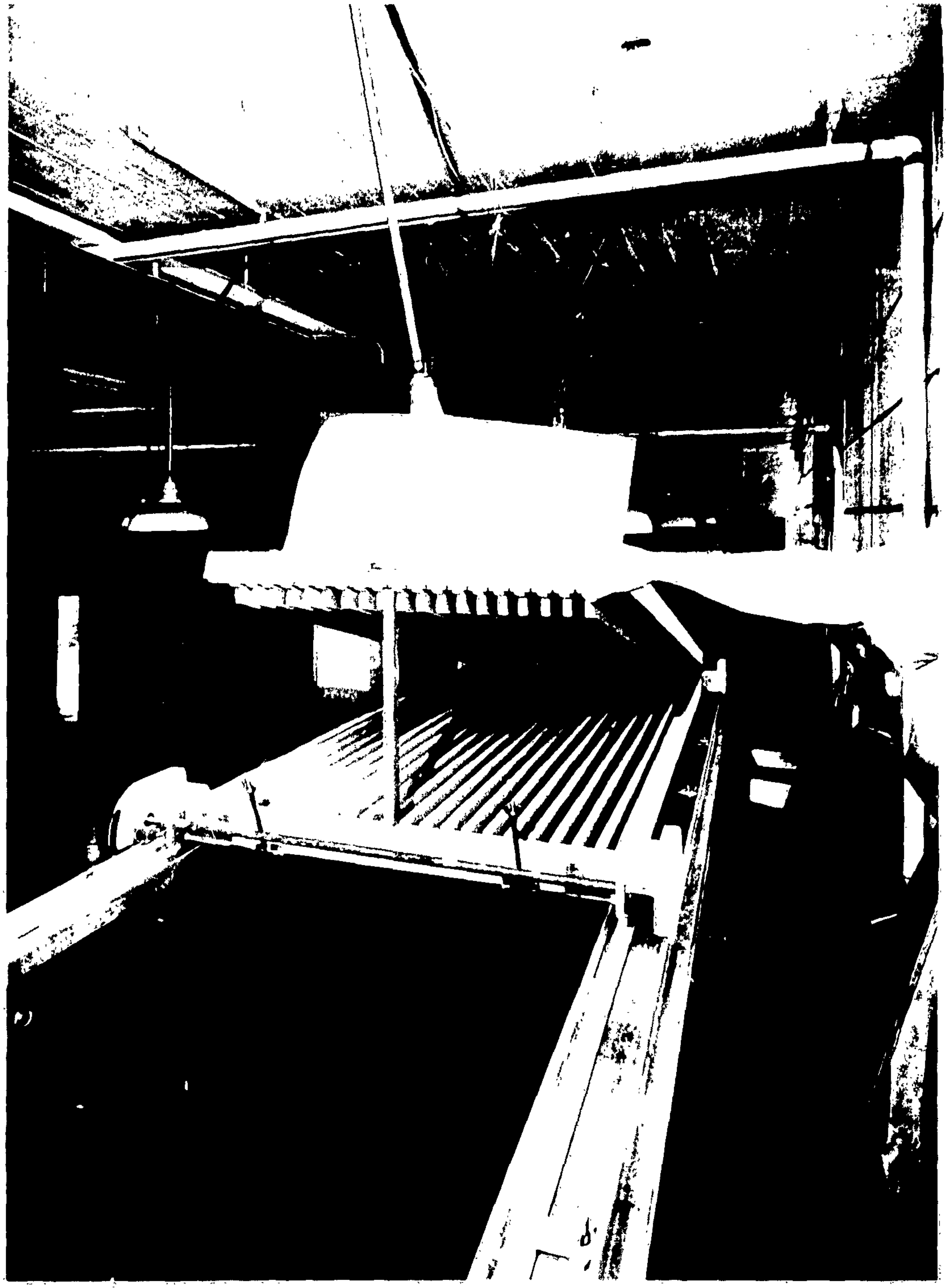

FIG. 6. Bead Dropper, Still-Water, Motion-Picture Technique.

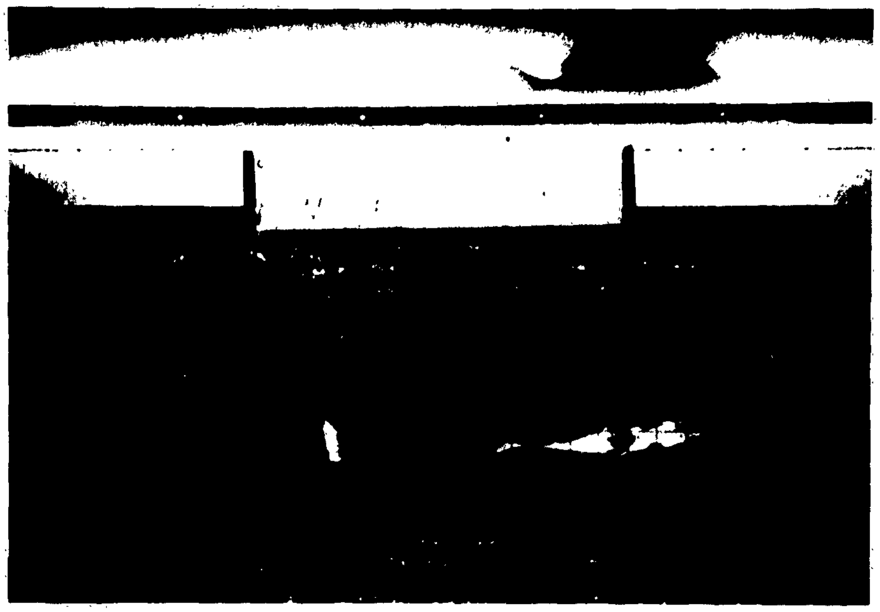

FIG. 7. Fish, Still-Water, Motion-Picture Technique.

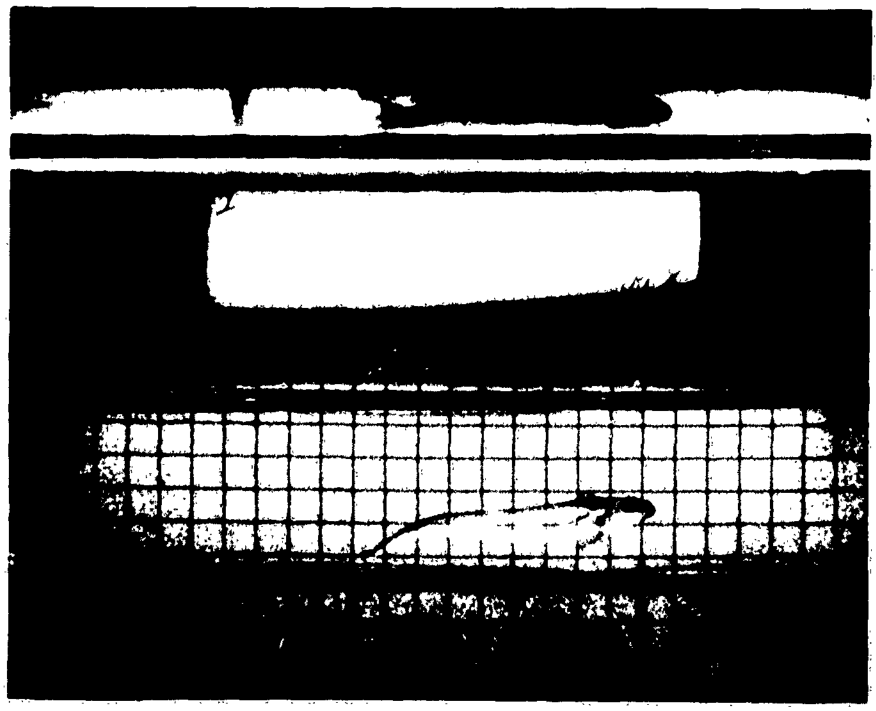

FIG. 8. Fish, General Swimming Behavior Study.

However, a general description of the Schlieren system is given with some elaboration on novel and unique features of the equipment.

Observation of the boundary layer phenomenon was accomplished using a standard, two parabolic mirror, Z configuration, Schlieren system. The parabolic mirrors were 12 inches in diameter and 72 inches focal length. Figures 9 - 11 illustrate the optical set-up, equipment, cameras, and static flume used in the Schlieren technique. The top parabolic mirror (Fig. 9) is used to collimate and direct the light from the light source to the second parabolic mirror. The collimated beam is then redirected, by means of a flat mirror, and focused on a knife edge so that approximately one-half of the concentrated bundle is stopped by the knife edge and the other half goes on to the camera. An adjustment of the knife edge cuts the light uniformly from the beam in the test section; however, any local refractive change in the test section disturbs the energy balance (by more or less of the rays hitting the knife edge) so that the local disturbance is seen darker or brighter than the background. The water can change its refractive properties if the density and, therefore, the refractive index is changed.

In order to record the boundary layer of the fish, the temperature of the fish is raised above the ambient temperature of the water in the test section. Then the heat transfer to the boundary layer from the fish changes the density of the water in the boundary layer. The refractive effect produced by the boundary layer is such that if the knife edge is parallel to the length of the fish, then the boundary layer on one side of the fish appears brighter and the other side of the fish darker than the background. If the knife edge is inverted--that is, swung 180 deg using the knife edge as a hinge point--then the previous bright boundary layer becomes dark and vice versa. Also, if the fish's temperature is lower than the ambient temperature of the water, the effect is reversed.

In order to photograph the boundary layer of the fish, the temperature of the fish is raised approximately 10°F by placing the fish in a separate warm-water holding box within the static flume. The gate to this box is then opened, and the fish swims down a chute past the test section into a deeper portion of the tank. The camera photographs a bottom view of the fish and the boundary layer on the side of the fish as the fish swims past the test section.

Some of the early work was performed omitting the knife edge in the Schlieren system. When used with a point light source, this provided a shadowgraph system (Fig. 12) of low sensitivity. At first, it was thought that a low sensitivity system would be desirable because of the thermal noise present in the water. However, in practice it was found that a high-sensitivity system was preferred because the thermal noise was a static effect and easily separated from the boundary layer phenomena.

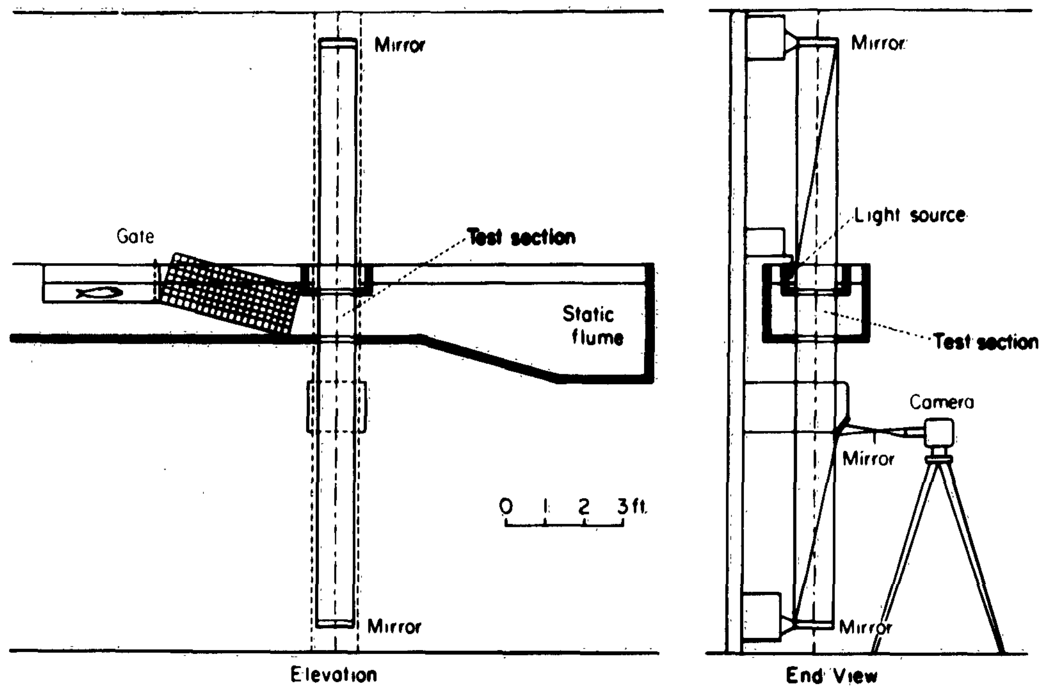

FIG. 9. Schlieren System

Four different light sources were used in this project. Three of the lamps were zirconium point sources--a 2-watt, a 25-watt, and a 100-watt. The fourth lamp was a specially fabricated 350-watt tungsten line source. The 2-watt point source (.003-inch diameter) was used in the early stages of the project. Its small size gave excellent definition in the shadowgraph system. In fact, the normal objective of the camera was not used in these tests, the image being cast directly onto the film. The 25-watt lamp (.029-inch diameter) was used for most of the 16-mm Schlieren work. The 100-watt lamp (.064-inch diameter) was used for only a short period of time. This lamp proved to be too large for knife-edge Schlieren studies; however, it would be an excellent lamp for studies using a circular mask in place of the knife edge. The 350-watt line source was used for color Schlieren and 35-mm sequence camera studies.

It should be pointed out that, in the Schlieren system previously described, the iris diaphragm of the camera lens functions as a field stop rather than an aperture stop. In other words, the diaphragm

FIG. 10. Schlieren Equipment.

FIG. 11. Warm-Water Holding Box and Schlieren Equipment, Schlieren Technique.

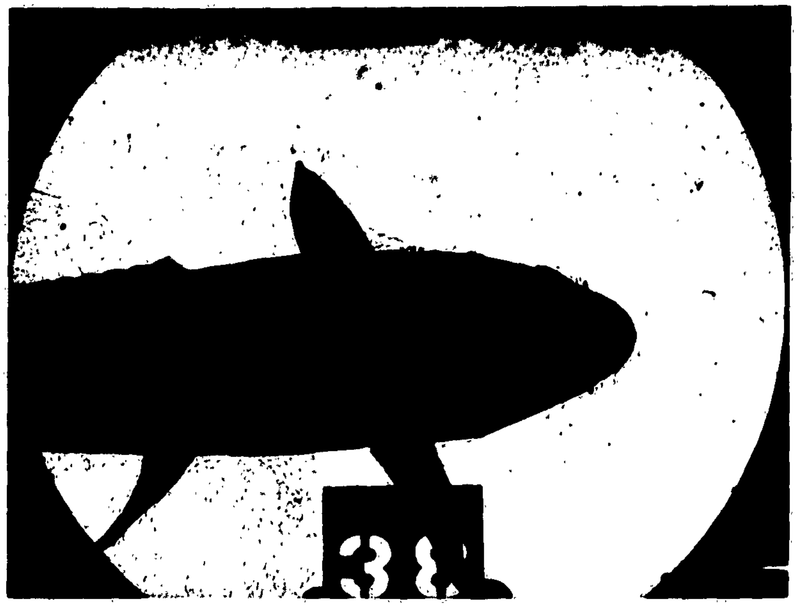

FIG. 12. Fish, Shadowgraph Technique.

controls or limits the field of view of the camera rather than the amount of light received by the film. This means that the exposure must be controlled by varying the shutter time, or by using neutral density filters, or by control of the light source. Also, contrary to conventional photography, the exposure time is proportional to image size or focal length of the camera lens. Thus, the 25-watt lamp was adequate for the 16-mm motion picture camera and the 350-watt lamp was necessary for the 35-mm sequence camera.

The 350-watt line source consisted of a tungsten filament, .025 inch in diameter and 2 inches in length. The filament was spring-loaded in tension and gas-cooled. The filament was mounted in a box equipped with a thin mylar window. Nitrogen gas was run continuously into the box, past the filament and then out again. The nitrogen excluded the oxygen and cooled the lamp. At some increase in gas flow, the mylar window could be eliminated, but the window did not appear to degrade the image so it was retained. The filament could be changed easily and generally needed replacing several times a day. The nitrogen bottle would last for about one day. The lamp took 9 volts at 40 amps, and it was only operated at full power for a few minutes each test run. The lamp could be run at low power indefinitely while adjusting the Schlieren equipment. The lamp was not only an inexpensive source, but a better color source than the usual Mercury arc. Under full power, the color temperature of the lamp was high enough that daylight type Super Anscochrome color film was used without the usual conversion filter for tungsten illumination. The high-output small-diameter filament was especially useful for the color Schlieren technique finally adopted.

The Schlieren color technique was a relatively new one in which the knife-edge was replaced with a grid of narrow color filters (Fig. 13). The light source may be focused on one of these color filters, or on the intersection of two colors, and as the beam is distorted by the Schlieren effect the disturbed rays are deflected onto different colored filters. A very narrow light source and filters are necessary to produce a sensitive system. The available filters were 1/16 inch wide and 1 3/4 inches long. They were glued to a common clear glass base and to each other, and the faces were ground and polished. The quality of the available filters was not satisfactory, and the intersection of colors was optically bad. The best results were obtained by covering the intersection of two colors (orange and green) with a mask that was slightly smaller than the image of the light source. The light source was adjusted on the mask until a very light green was obtained. Then a slight deflection of the rays produced an orange boundary layer on one side of the fish and a green boundary layer on the other side (see Fig. 14). The system worked, but it was not judged technically as good as the black and white system.

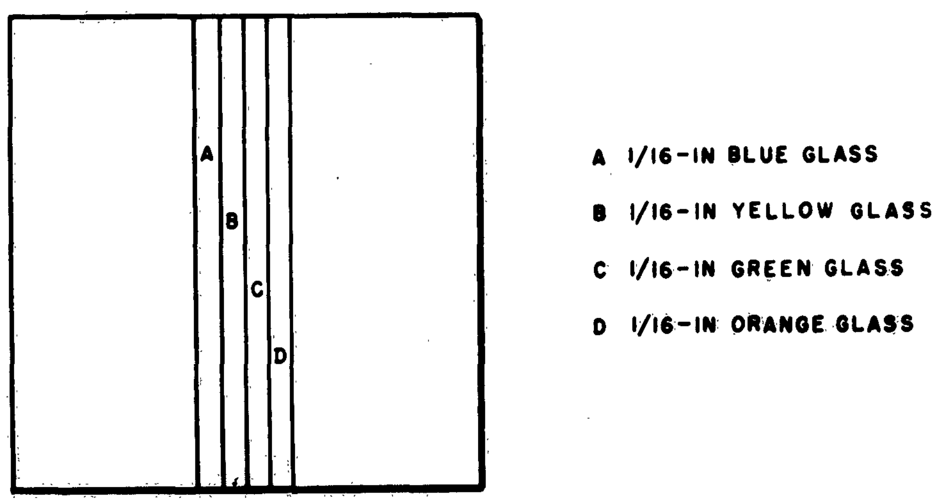

FIG. 13. Schlieren Color Grid.

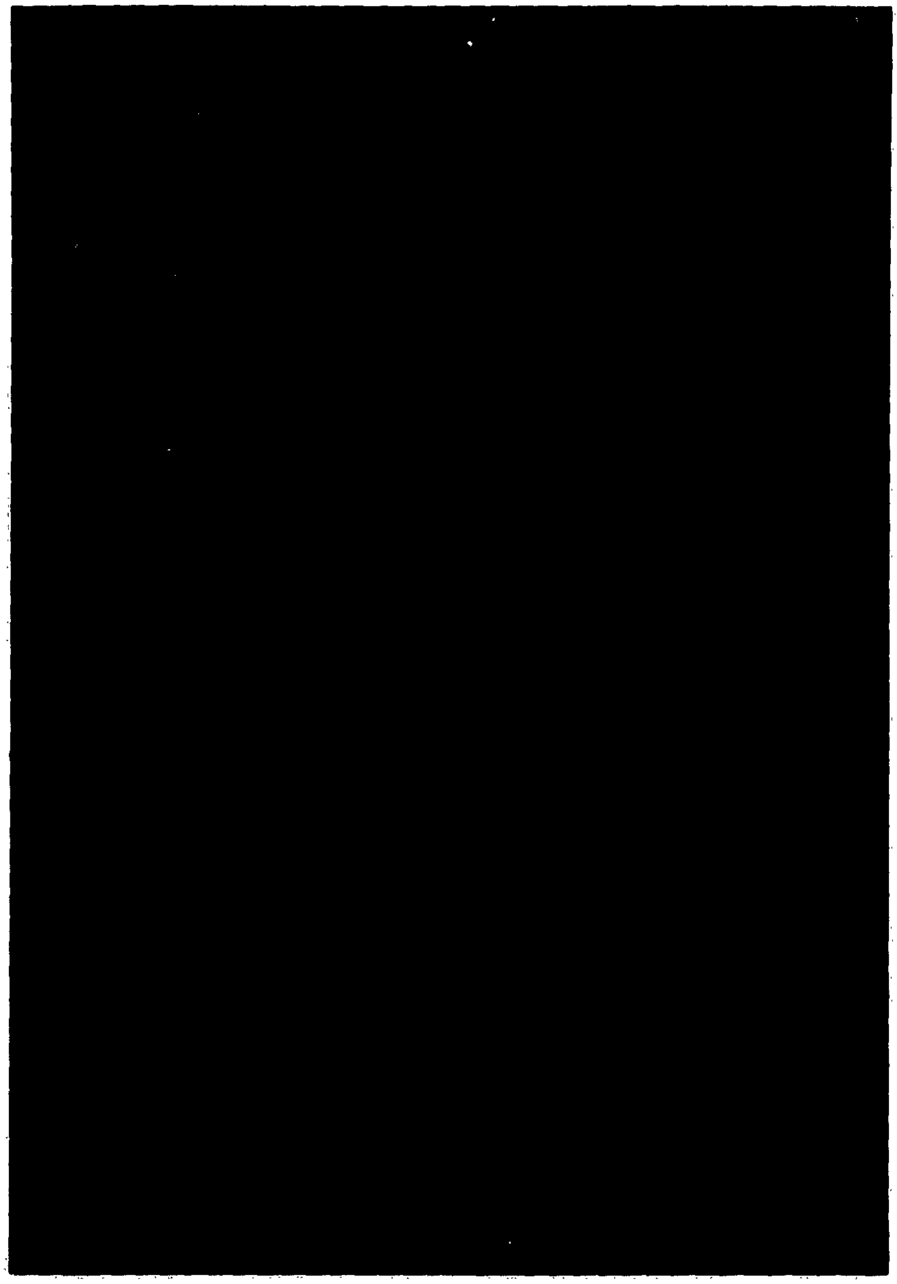

FIG. 14. Fish, Schlieren Color Technique.

PHOTOGRAPHIC EQUIPMENT

A 16-mm DBM 5 Milliken high-speed cine camera was used to record most of the Schlieren data. This camera uses an intermittent movement with pin registration. It was operated at 400 frames per second. The camera was equipped with a 67-mm focal length lens. The rotary shutter's open sector was 36 deg wide providing a 1/4,000-sec exposure time. The 25-watt point light source provided enough light to expose correctly Plus-X black and white and Super Anscochrome color film. The 350-watt lamp was balanced to the 16-mm camera by means of a filter which decreased the light by a factor of 10.

Earlier, a 35-mm Mitchell (128 fps) and a 35-mm 4B Photosonics (500 fps) cine camera were used. The 35-mm camera gave superior pictures when properly exposed; however, the lack of 35-mm processing facilities in Seattle, Washington, and the lack of adequate viewing facilities forced the use of 16-mm cameras. Half-day 16-mm processing service in Seattle was extremely helpful in monitoring the results. This service permitted a control over 16-mm techniques that gave results close to the best which were achieved sporadically with the 35-mm cine cameras. Also, the 16-mm cine camera permitted the use of positive reversal film that was judged to be superior to negative films.

The 16-mm cine camera had a major disadvantage in that the frame size was too small to procure adequate still enlargements. Because of this, a 35-mm sequence camera was designed and fabricated in the double frame size. The camera was equipped with a 300-mm focal length lens; thus, the image size was about 20 times the area of the 16-mm image. The camera was operated at 30 frames per second with a 2-deg rotary shutter (1/5,000-sec exposure). The efficiency of the 2-deg shutter was good because it was large (12-inch diameter) and because the Schlieren beam limited the relative aperture of the lens to a very low value. A good exposure could be obtained with either Plus-X black and white or Super Anscochrome color film using the 350-watt lamp. The camera used conventional 35-mm 36-exposure cassettes; thus, the processing of the short length 35-mm film could be done in Seattle by the normal 35-mm still processors. The short length film limited the total operating time of the camera to about 1 second or 30 frames. The mechanical parts of the camera ran continuously so that the film advance could be started and stopped within one frame interval. The operator could trigger the film advance mechanism remotely, and after 30 frames the mechanism would stop automatically. The camera was quite large and rather crude in construction but adequate for the special work for which it was designed.

FISH BEHAVIOR

Considerable trouble was encountered in training fish to swim by the Schlieren test section. However, once the proper technique was found, it was relatively easy to condition a fish to the requirements. As a result of much experimentation, the following technique was adopted. The fish was kept in a warm water box located near the surface of the water in the flume (Fig. 9 and 11). A confined channel led from this box down past the test section and then down into a deep dark portion of the flume. The fish's natural reaction to flee to deep water was then used to advantage, since the only way to the deep water led through the Schlieren test section.

To initiate the event, a bright light was turned on to the holding box at the same time that the gate to the box was withdrawn. Very shortly after the light was turned on, the fish was mildly shocked with an electric prod. Within three or four trials, the fish learned to associate the light with the shock and often left the box without use of the electric prod. An electric fence arrangement in the test section was sometimes used to keep the fish centered in the test section. This arrangement worked quite satisfactorily, although there was little or no control of the fish's speed or swimming mode.

BOUNDARY LAYER PHENOMENA

Unfortunately, it is not always possible to illustrate in a report the same phenomena observed on the motion picture screen. The quality of motion adds much to the observation of the event, and the continuous changing of frames minimizes the poor resolution and defects of the 16-mm cine film. Therefore, it is necessary to describe that which cannot adequately be pictured. However, some of the events were caught on the 35-mm sequence camera so that a limited number of illustrations can be shown.

Experiments were run to verify that the observed laminar layer was actually the fish's boundary layer. It was easy to show that the Schlieren system responded to thermal gradients. If a hand or finger was placed in the test section, the thermal effect was quite pronounced. As the hand chilled, the effect diminished. A stick produced little or no effect if it was allowed to assume the temperature of the water. Some motion pictures were taken of a fish which had been maintained at the test section temperature. These pictures showed that in spite of using the Schlieren system at its highest sensitivity, practically no boundary layer effect was observed. A warm fish was photographed in which the Schlieren knife edge was set perpendicular to the length of the fish; the effect was quite small and mainly visible on portions of the fish parallel to the knife edge. When the knife edge was oriented parallel to the length of the fish, a bright border could be seen on one side of the warm fish. If the knife edge was inverted, then the bright border would change to the other side of the fish. If the fish was cooler than the water in the test section, then the bright border would appear on the opposite side to that of a warm fish. There seemed to be no question that the boundary layer was made visible by the Schlieren technique.

Both laminar and turbulent boundary layers were observed on the same fish. A fast fish would have an almost complete laminar boundary layer. A slow fish would generate considerable turbulence. Slowly swimming fish were often observed to be discharging water from their gills. This discharge was always turbulent and mingled with the boundary layer along the side of the fish. The area behind wounds and protuberances was always turbulent, although the flow usually became laminar again. In the case of model submarines, the flow was usually quite laminar until it broke away from the body near the tail. Several rather interesting flat plate runs showed a remarkable transition of the boundary layer from a laminar to a turbulent phase. At first, little wavelets could be seen to build up in the laminar layer, then the wavelets would crest and break producing a completely turbulent boundary layer. This action was observed to occur simultaneously over the entire surface of the plate. The entire action took place in approximately 1/50 second. The transition was triggered as the plate decelerated at the end of its run. A slight positive angle of attack was found to help considerably in initially establishing a laminar flow over the flat plate.

The boundary phenomena of fish, a model submarine, and a flat plate are illustrated in the series of photographs (four frames each) in Fig. 15-20.

CONCLUSIONS AND RECOMMENDATIONS

The flow marker techniques were considered inadequate because the fish could not be trained to swim properly through the markers. In fact, the Schlieren techniques showed more promise of showing the general flow pattern than the flow marker techniques. Quite often the Schlieren techniques showed large irregular static thermal lines in the water. These thermal lines were displaced by the fish and showed some of the gross flow around the fish. On some occasions, the boundary layer flow left trailing vortices in the wake of the fish. It is believed that a large Schlieren system could be developed specifically for viewing general flow patterns. A system with a 24- to 36-inch diameter field of view could be used with the artificial generation of thermal lines as flow marking lines. The system would probably be more practical in a low-turbulence moving-water flume than in still water. Then the operation would be very analogous to the operation of a smoke tunnel. By a copying process, it would be possible to make the water appear to be still with the fish moving, since this is a more desirable viewing relationship for analysis of the patterns. A similar system using dye or bubble generation as flow lines would probably be incompatible with training of the fish.

The Schlieren boundary layer technique was successful in revealing boundary layer phenomena. The technique is quite powerful and should be widely applied to boundary layer studies. During the course of its development, over 200 data runs were made of various models and living fish. A detailed study of these runs is now underway. Unfortunately, the low Reynolds number of most of these runs is in the region where laminar boundary layer is normally expected. High Reynolds number, where turbulent boundary layers are expected, would require larger and faster fish. According to boundary layer theory, laminar boundary layers are to be expected with trout even at maximum speed; whereas, turbulent boundary layers would be expected with high-speed dolphins. However, there is reason to believe that dolphins remain laminar at high speeds. The Schlieren technique could give direct evidence as to the boundary layer condition.

It is believed that Schlieren techniques have progressed to a point where worthwhile boundary layer records could be taken of high-speed dolphins. The experiment would require a large body of water to give the dolphin enough swimming room and an underwater Schlieren system. The dolphin is a warm-blooded mammal, so it is expected that a high-sensitivity Schlieren system in cool water would reveal the boundary layer. The optical and camera equipment would be placed in an underwater chamber with a 6-ft test section water gap for the dolphin to swim through. Preferably, a cool, clear, shallow section of open ocean would be the most desirable area to conduct such a test, if the dolphin would remain a voluntary captive. Failing this, a large channel might be located that would be capable of closure either by mechanical means or by the use of sonic or electric fences. It is highly recommended that further work be conducted in this field.

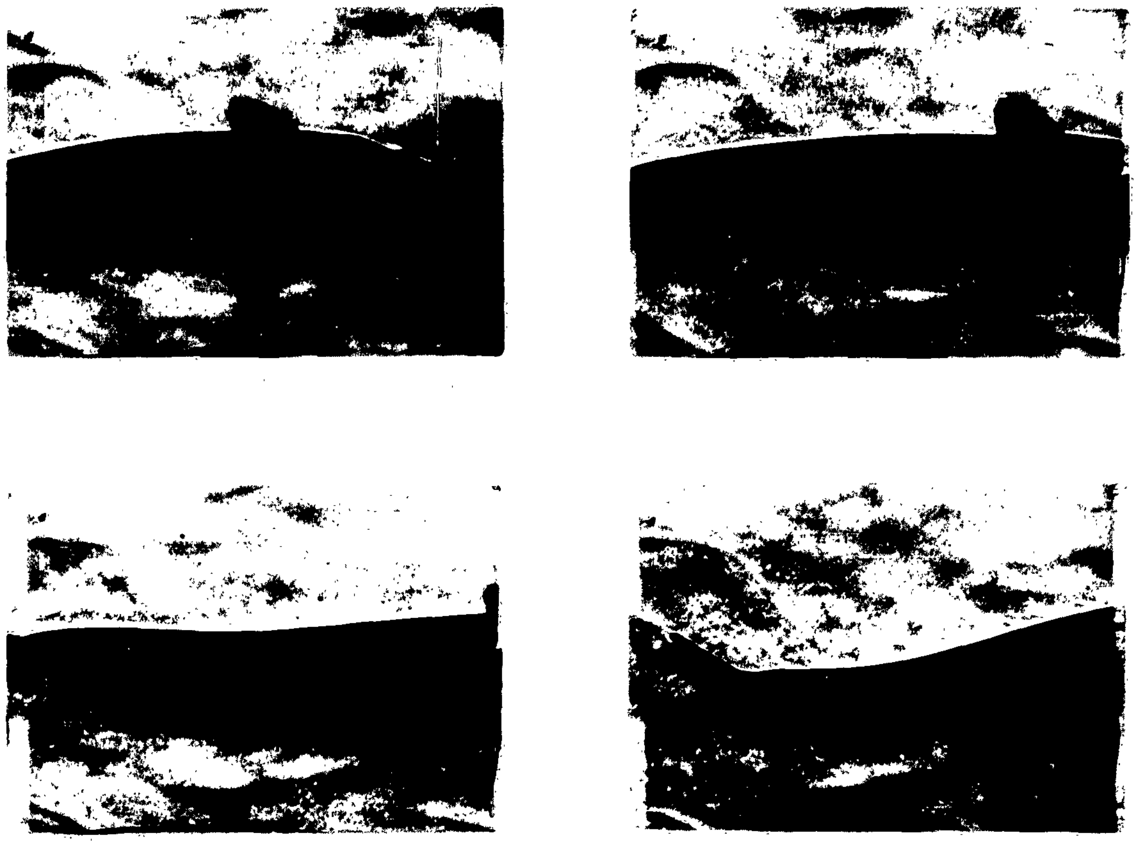

FIG. 15. Turbulent Boundary Layer of Fish, 10 frames/sec, Schlieren Technique.

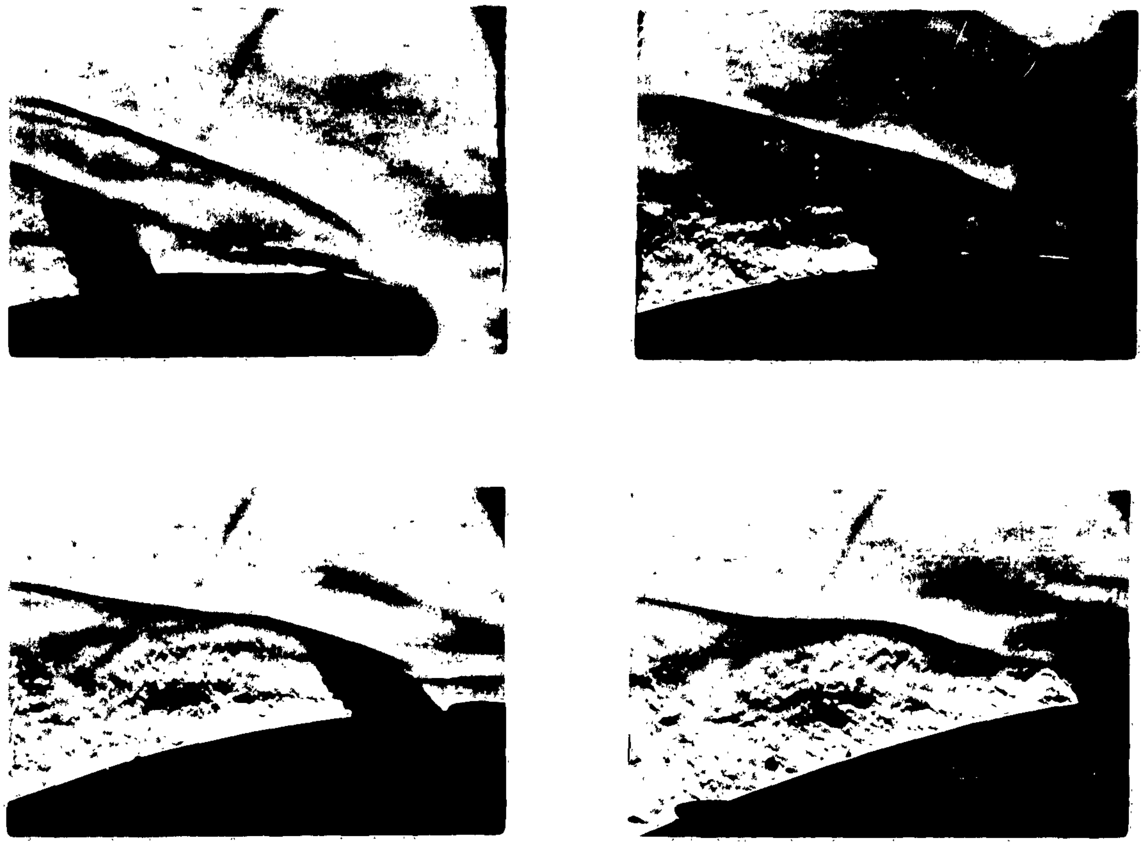

FIG. 16. Turbulent Gill Discharge of Fish, 15 frames/sec, Schlieren Technique.

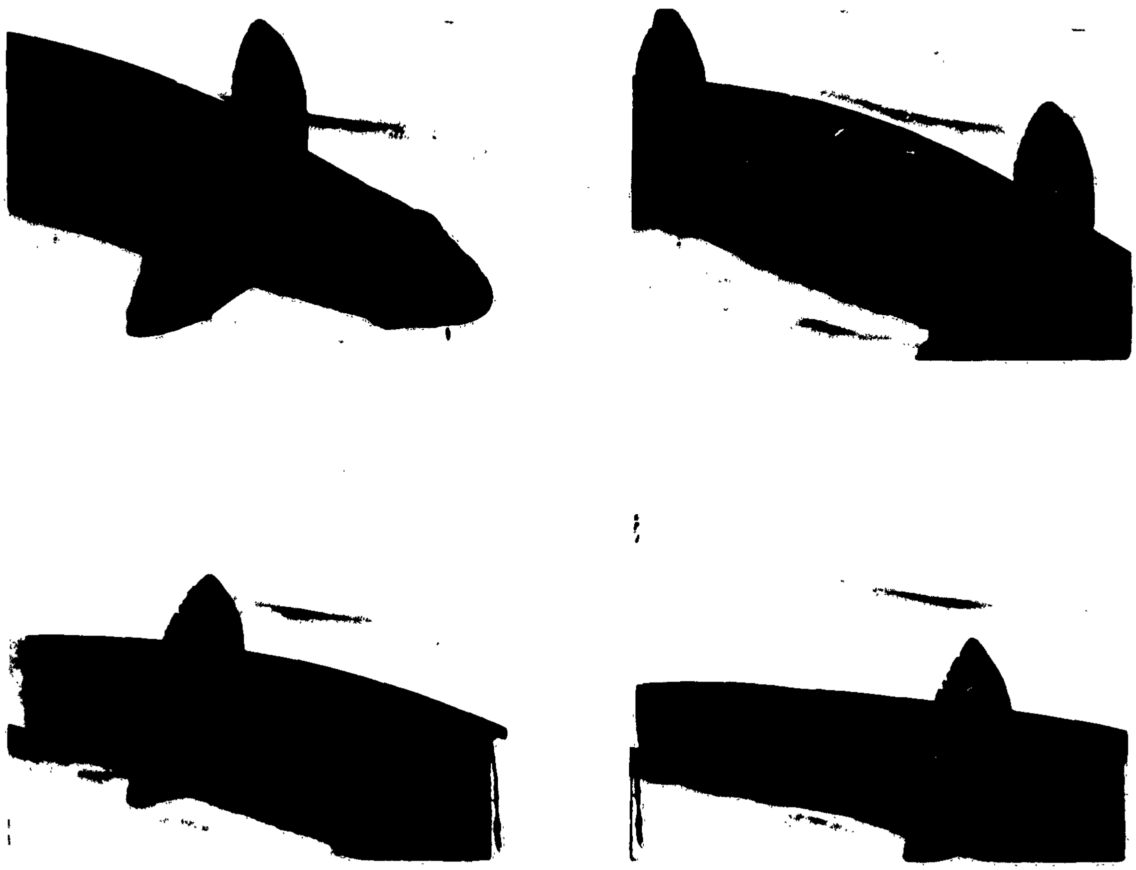

FIG. 17. Transition of Laminar to Turbulent Boundary Layer of Fish, 15 frames/sec, Schlieren Technique.

FIG. 18. Transition of Boundary Layer Caused by Protuberance Near Nose of Fish, 15 frames/sec, Schlieren Technique.

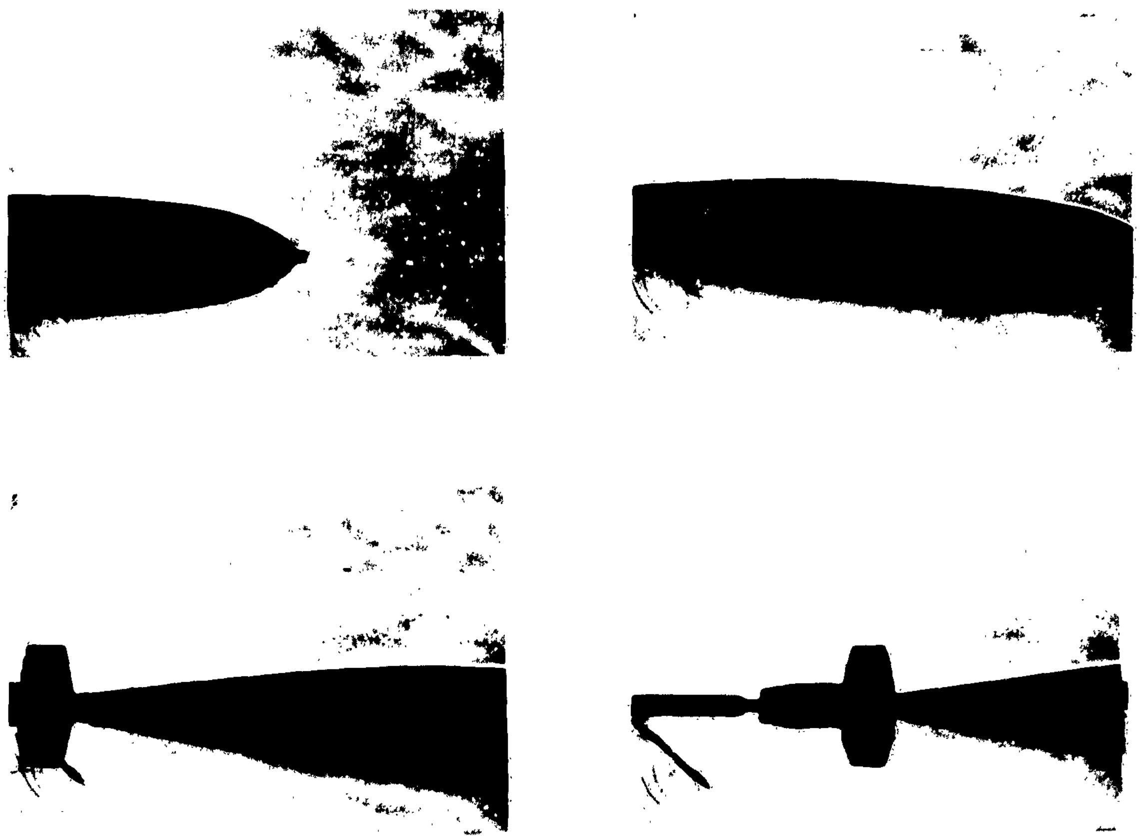

FIG. 19. Laminar Boundary Layer Showing Detachment Near Tail of Model Submarine, 15 frames/sec, Schlieren Technique.

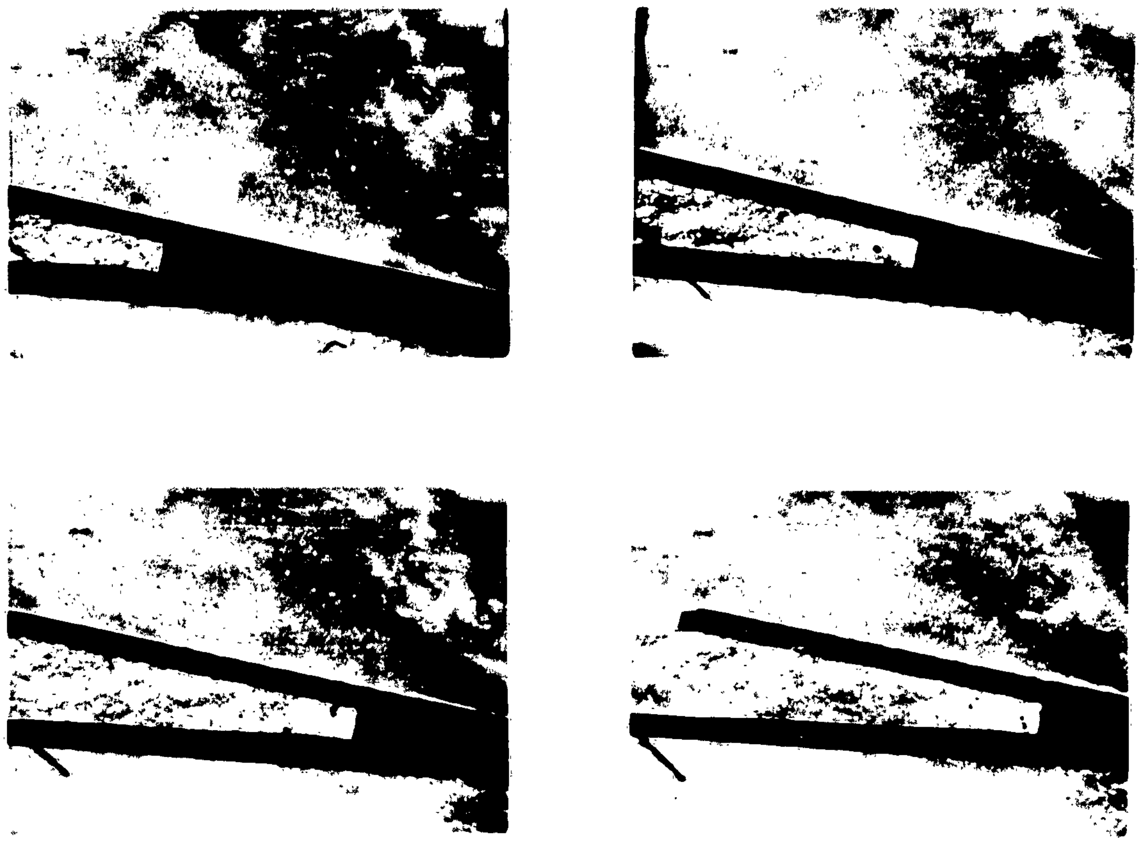

FIG. 20. Transition of Laminar to Turbulent Boundary Layer of Flat Plate, 15/frames/sec, Schlieren Technique.

REFERENCES

1. National Gas Turbine Establishment. The Development of a Flow Visualization Technique, by E. C. Roberson. Ministry of Supply, Gr. Brit., NGTE, November, 1955. (Report No. R181, ASTIA AD 83866).

2. U. S. Naval Ordnance Test Station. Flow Visualization Studies: Interim Report, by Leroy Doig, W. H. Allan, and Howard R. Kelly. China Lake, Calif. NOTS, 18 July 1960. (NOTS IDP 1043).

3. U. S. Naval Ordnance Test Station. A Method for the Production of Uniform Beads of Controlled Density in the Density Region Close to Unity, by Arnold Adicoff. China Lake, Calif. NOTS, 8 August 1959. (NAVORD Report No. 6580, NOTS TP 2308).

4. University of Washington, College of Fisheries. Technique for the Visualization of the Flow Pattern Around Salmonoid Fish, by Joseph C. Kent, Dan W. Clancy, Gerald J. Paulik, and Allan C. DeLacy. Seattle, Washington, UW, November, 1959. (Termination Report for U. S. Navy Contract No. 123(60530)20579A).

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